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A Laser Technique for Investigating the Effects of Thermal Transients on Pressure Transducer Performance Characteristics

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[3] Located at Boulder, Colorado 80302.

A Laser Technique for Investigating the Effects of Thermal Transients on Pressure Transducer Performance Characteristics

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FOREWORD

The work described was performed as a task within the Inter-Agency Transducer Project. This is a continuing project for the development of calibration and evaluation techniques for electromechanical transducers, and is supported by a number of government agencies. This task was funded by the U. S. Atomic Energy Commission through the Lawrence Radiation Laboratory of the University of California under order number SAN-71-325.

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A Laser Technique for Investigating the Effects of Thermal Transients on Pressure Transducer Performance Characteristics

Paul S. Lederer and John S. Hilten

A simple and repeatable testing technique was developed which makes it practical to obtain information on the zero shift and change in sensitivity of a pressure transducer while it is subjected to a thermal transient generated by a mechanically chopped cw laser beam. Several commercial, flush diaphragm, pressure transducers with ranges up to 50 psi (3.45×10^5 N/m^2) were tested and showed zero shifts and changes in sensitivity of the order of 20% FS due to thermal transients with power densities up to 100 k W/m^2. The transducer under test can be pressure cycled while it is irradiated. In this way, zero shifts and sensitivity changes may be directly displayed in a procedure which requires a testing time of only about one minute.

Key words: Laser; performance characteristic; pressure transducer; temperature effects; test method; thermal transient.

1. Introduction

Pressure transducers are often exposed to rapidly changing temperature conditions, while measuring gaseous pressures. Such conditions prevail in measurements of nuclear or high explosive blasts, rocket-and jet engine parameters, shock tube phenomena, and nuclear reactor performance. The performance characteristics of pressure transducers, at other than the laboratory ambient temperature, are almost always specified with reference to equilibrium conditions, that is, conditions in which the temperature is uniform throughout the instrument. Transducers are generally designed to operate within an acceptable error band over a substantial range of temperatures. The design is also based on the assumption that the entire transducer is allowed to reach a uniform and stable temperature in operation. Exposure of the transducer to thermal transients, however, may result in large measurement errors, caused by the temperature gradients set up within the transducer. Such gradients can cause nonuniform stresses in the sensing elements, changes of elastic properties and resistance changes in electrical components. The sensing ability of the transducer may be seriously impaired by these thermal gradients until a state of thermal equilibrium is reached. In practice, this may be a matter of several minutes, during which time meaningful pressure data may be lost.

Test procedures to establish the effects of equilibrium temperatures on transducer performance characteristics ("Static" Temperature Tests) are well established and described in the literature[1,2].[1] A limited test method to investigate the effect of thermal transients on the zero pressure output of a sensor was developed at the National Bureau of

[1] Figures in brackets indicate the literature references at the end of this paper.

Standards[3]. A number of commercial transducers were tested using this method, and the results for many of them indicated very large changes in zero pressure output due to the thermal transients[4].

This test method involved dipping the diaphragm end of the sensor into a pool of molten Wood's metal and recording the resultant output signal. The method did not attempt to simulate the actual operational environment, but served as a useful comparison technique in transducer selection. It only permitted study of the zero pressure characteristics, since the system could not be pressurized. Since the knowledge of the effects of thermal transients on sensitivity was also considered very important, attempts were made to devise an evaluation technique which would achieve this goal as well. The advent of the continuous wave laser, as a controllable source for a substantial amount of radiant thermal energy, provided the basis for the practical, simple and efficient evaluation technique described below.

The method developed uses the narrow beam of infrared radiant energy from a continuous wave (cw) laser. Mechanical interruption of the beam produces the transient signal required for the test. The beam passes through a transparent window into a cavity, which can be pressurized, to impinge on the diaphragm of the transducer under test. Proper choice of the glass of the window permits most of the radiant beam energy to reach the transducer. With cavity at zero pressure or at the transducer's full scale pressure, or cycled between these values, the transducer output is first displayed on a graphic recorder without irradiation of the diaphragm. After a few seconds, the radiant energy is applied to the transducer by raising the mechanical shutter which normally blocks the beam. The effects of the resultant thermal transient can be observed from the recorded transducer output. The technique was designed primarily for flush diaphragm pressure transducers. The entire experimental setup is shown in Figure 1. A schematic of the arrangement of components for this experimental technique is shown in Figure 2.

2. Test Equipment

2.1. Laser System

A continuous wave (cw) neodymium-YAG (yttrium- aluminum garnet) laser was used for all tests. The laser rod is energized by the light from two krypton arc lamps. By varying the electrical power input to the arc lamp, the optical output power in the laser beam can be varied. The system is capable of operating at a maximum electrical power level of about 5600 watts (both lamps on), which is stated to produce about 60 watts optical power in the beam. The system can be operated at reduced power levels with one arc lamp only. The wave length of this laser is 1.06 μm, in the infrared part of the spectrum. The beam diameter is specified not to exceed 5 mm (3/16 in.) at the source; 90% of the beam is stated to be within an angle of 2.5 degrees. The laser system consists of the laser head assembly, a unit about 12.7 cm x 12.7 cm x 46.7 cm (5 in. x 5 in. x 18 in.) mounted on an aluminum channel, and of the power supply and heat exchanger assemblies.

2.2. Transducer Test Fixture

The test fixture is a rectangular brass block, approximately six inches high, four inches wide and deep, mounted on a pair of aluminum rails on which the shutter assembly and the laser head with its aluminum channel support are also mounted as shown in Figure 3. Figure 4 shows the cross section of the test fixture. In the front surface of the block facing the laser head is a sealed, round glass window with an aperture of 3 cm (1-3/16 in.) as shown in Figure 5. The window glass is of a 96% silica composition with a low coefficient of expansion. A circular hole with a diameter of 3.8 cm (1-1/2 in.) in the rear face of the block is coaxial with the glass window. The transducer to be tested is mounted in a brass plug (see Figures 3 and 5) and the brass plug is then inserted in the hole in the test fixture. This mounting arrangement is not dissimilar to the actual transducer mounting when used for pressure measurements. The use of plugs facilitates the testing procedure. With the plug securely held in the fixture, the small volume between transducer diaphragm and glass window can be pressurized rapidly.

The entire fixture can be moved on the aluminum rails toward and away from the laser head. It can be locked in position with a bolt, although this was not found to be necessary during tests due to the weight of the fixture. The fixture was painted black with a nonreflective paint to minimize stray laser beam reflections.

The valves necessary for the cyclical application of pressure to the test transducer are mounted on the test fixture and may be seen in Figure 5. This was necessary in order to keep the volume, which was to be periodically pressurized, as low as practical to achieve an adequate rate of cycling.

2.3. Shutter

The shutter, which is used to interrupt the laser beam, is a simple mechanical lever pivoted about an axis parallel to the beam and about 7-1/2 cm (3 in.) from it. See Figures 3 and 5. The lever expands into a circular disc about 5 cm (2 in.) in diameter covered with a disc of asbestos cement sheet on the side facing the laser. In operation, the outer end of the lever is depressed manually, raising the disc and permitting the beam to impinge on the transducer. It is a fail-safe device, since release of the lever will cause the disc to drop into a position to intercept the beam. The aluminum shutter assembly is also painted black, and may be set at different distances from the laser head.

2.4. Recording System

The output of the test transducer was recorded by a sensitive, large deflection, differential x-y recorder with a maximum sensitivity of 50 microvolts per centimeter, using 28 x 42 cm (11 in. x 16-1/2 in.) paper. The recorder also has a built-in time base with rates ranging from 0.02 to 5.0 centimeters per second. This instrument was selected

on the basis of the high resolution, high input impedance, and ease of recording offered by this system over a galvanometer recorder or an oscilloscope.

2.5. Power Meter

The optical power output of the laser was measured with a broadband absorption meter specifically designed for measuring the output of cw full scale power ranges from 1 to 100 watts. The meter consists of a convection cooled, direct absorption head with a circular aperture of one inch diameter, cable connected to the control unit which has the read-out meter. Both can be seen in Figure 1.

2.6. Transducer Excitation

All transducers tested were strain gage types. A high stability electronic power supply with a range of 0 to 40 V and 0 to 500 mA was used to supply the required constant voltage excitation. The power supply is equipped with a digital voltage programmer which greatly simplifies the setting of the proper transducer voltage.

2.7. Pressure Calibration System

The instrumentation console is equipped with a commercial pressure regulator with a range up to 6.89×10^5 N/m^2 (100 psi) from which the test pressure is obtained. A precision dial pressure gage with a range of 0 to 3.45×10^5 N/m^2 (0 to 50 psi) and an uncertainty of 0.1% was used to measure and calibrate the recorder, since the full scale range of the transducers tested did not exceed 50 psi.

3. Experimental Determination of Laser Characteristics

3.1. Test Procedures

The specifications of the laser describe the beam diameter as not exceeding 5 mm (3/16 in.) at the source, and 90% of the beam to be within an angle of 2.5°. Based on this, the beam should then be roughly 2.5 cm (1 in.) in diameter at a distance of 48.3 cm (19 in.) from the end of the laser head. Since the glass window has a diameter of 3 cm (1-3/16 in.), just about all of the beam should therefore impinge on the transducer and its mount. Most of the transducer tests were conducted at this distance.

A series of experiments were performed to determine those laser characteristics pertinent to the transducer thermal transient tests. In all cases optical beam power was the quantity measured with the absorption power meter.

In the initial test, the optical power was measured as a function of electrical power at various distances from the source. In this test, the power meter was placed directly behind the transducer test fixture

and lined up so that the absorption head aperture was coaxial with the laser head aperture. The transducer mounting plug had been removed so that the beam would pass first through the 3 cm (1-3/16 in.) diameter glass window, then through the 3.8 cm (1-1/2 in.) diameter circular hole in the fixture and finally into the 2.5 cm (1 in. diameter) absorption head aperture. The design and size of the absorption head are such that the absorption surface had to be placed 8.25 cm (3 1/4 in.) behind the normal location of the transducer diaphragm. Tests were run with the absorption head sensing surface at distances of 79.4 cm, 66.7 cm, and 56.5 cm (31-1/4 in., 26-1/4 in. and 22-1/4 in.), from the laser head front surface. The resultant data, plotted in Figure 6, show that optical power does not keep increasing linearly with increasing electrical power.

A second test was run with a brass transducer plug in the test fixture. This plug had a 1.27 cm (1/2 in.) diameter hole in its center. Any portion of the laser beam passing through this hole would then represent the radiant energy which would actually impinge on the 1.27 cm (1/2 in.) diameter transducer diaphragm during the thermal transient test. Three of the transducers tested have sensing diaphragms of this diameter. Again the absorption head of the power meter was placed immediately behind and adjoining the test fixture. Tests were run at the above distances. The power levels measured are also plotted in Figure 6.

The results of this test emphasize the previously observed nonlinearity between electrical power and apparent optical power even more. We decided, therefore, to investigate more closely the energy distribution in the laser beam.

An extensive series of tests were performed using eight brass plugs with concentric holes of varying sizes, the ninth hole being that of the fixture itself. These tests also encompassed six different power levels and five different fixture-to-laser-spacings (six for several tests). Data from these tests are plotted in Figures 7 and 8. An additional series of tests at two power levels and two distances was performed without the glass window in place to assess the effect of the presence of the glass on the transmitted beam energy. These data are plotted in Figure 9. In the graphs, the measured optical energy is plotted versus hole area (in square centimeters for subsequent interpretation in terms of beam energy density) in Figures 8 and 9.

Since most of the transducer tests were made with transducer diaphragms of 1.27 cm (1/2 in.) diameter and 48.3 cm (19 in.) from the laser corresponding to an absorption head sensor distance of 54 cm (21-1/2 in.), the relation of optical to electrical power was investigated more closely for these conditions. A series of measurements were made using first one of the krypton lamps at a time, and then both, to excite the laser rod. Results are shown in Figure 10.

3.2. Test Results

The graphs in Figure 6 indicate quite clearly that the laser beam tends to increase in diameter as the electrical input power increases. If one considers the optical power measured through the 1.24 cm^2 port area (1/2 in. diameter), this power appears to increase linearly with electrical power until an input level of about 2000 watts is reached. Beyond about 3000 watts, additional electrical input power does not produce any further increase in optical power. It can also be seen that this characteristic becomes more pronounced as the distance between test fixture and laser head is increased. A very similar situation prevails for a port area of 11.4 cm^2 (1-1/2 in. diameter) also shown in Figure 6. The only difference is that the "flattening" of the characteristic curves begins at a much higher input power level, above 3000 watts. While the characteristics observed in the latter case might be attributed wholly to the inability of the absorption head with its one-inch diameter aperture port to capture all the laser beam energy, this clearly cannot be the explanation for the characteristics observed with the half-inch diameter port in the test fixture. In this case the absorption head aperture is only about 3.8 cm (1-1/2 in.) behind the port opening, and thus highly unlikely to miss intercepting any portion of the laser beam which passes through that port.

The results from the more detailed investigation which followed confirmed the above results. The data plotted in Figure 7 indicate that beam energy is almost independent of distance between absorption head and laser head at low power levels. This relationship appears more pronounced with larger fixture port areas. The curves also indicate that for the 1.24 cm^2 area one does not really have to make corrections, at the power levels used in the actual tests, for the fact that the transducer diaphragm is 8.25 cm (3-1/4 in.) closer to the laser head than the absorption head sensing surface. The power levels during transducer tests did not exceed 2000 watts. The power meter is described as having an accuracy of $\pm$ 5%, and the repeatability of the laser output power, as measured, is within 3%. We decided not to make the correction, but use the measured value of laser power through a specified hole area as that actually impinging on the transducer diaphragm of the same area.

The curves in Figure 8 indicate several things. Beam power varies linearly with hole area, even up to areas somewhat greater than 1.24 cm^2 (corresponding to the typical 1/2 in. diameter diaphragm). The linear relation extends to larger hole areas at higher power levels. This suggests that the energy distribution in the center of the beam is uniform and that the region of uniformity increases in diameter as the power level increases. At the same time the diameter of the total beam increases with increasing power level. The graph also shows that at the lower power level apparently all of the beam energy is intercepted by the absorption head, since the readings are the same for the larger hole areas regardless of distance. This is apparently not the case at a high power level (near 4000 watts). The actual electrical power levels measured varied slightly during the experiments, as indicated by slightly

different lamp voltages when the input current to each lamp was set to the same value. Voltage and current for each lamp were measured with the meters built into the laser control console. The product of the meter readings was reported as the electrical input power. Whenever the test fixture was moved, the electrical power to the laser was turned off for safety reasons. When it was turned on again, the power level was frequently found to be slightly changed. Variations in optical power output were found to be within less than 5% as shown in Table I.

The experiment leading to the graphs of Figure 8 was repeated without the glass window. The results, plotted in Figure 9, show curves quite similar in shape to those of Figure 8. The major difference is in the magnitude of the optical power levels. Presence of the glass window in the path of the laser beam attenuates the beam power on the average by about 7%.

TABLE I

Repeatability of Laser Power Output Measurements
Taken Six Days Apart

Hole Area cm^2	Electrical Power watts	(1) Optical Power watts	(2) Optical Power watts
0.176	3880	1.2	1.2
1.24	3880	8.2	8.0
2.17	3880	12.7	12.7
3.24	3880	17.0	17.5
11.4	3880	22.0	22.0

On the basis of these tests, we concluded that tests on pressure transducers with 1.27 cm (1/2 in.) diameter diaphragms at a nominal distance of 19 inches from the laser head would insure a laser beam of adequate diameter to irradiate the diaphragm, but not too large to miss being wholly intercepted by the absorption head, and of relatively uniform energy distribution. This would, however, only be true at electrical input power levels up to about 2000 watts. Accordingly, a final series of tests for these conditions was made to investigate in greater detail the relation of optical to electrical power. These results are shown in Figure 10. The laser rod is energized by two krypton flash lamps which may be used singly or together. The plotted test results show the variations in optical power obtained for the same electrical input power depending on the lamp configuration used. The data also show the previously observed linearity up to an optical power output of nearly 12 watts, corresponding to an electrical input power of about

2000 watts, and the roll off beyond that point. The fact that there is no optical output at electrical power levels below about 600 watts is due to the fact that the krypton flash lamps will not remain lit at any lower electrical power. This was confirmed visually.

The optical power values used in the subsequent transducer tests were obtained from the data in Figure 10. A brief test on laser output repeatablility shown in Table I indicates level changes of less than 3% for measurements performed six days apart.

4. Experimental Determination of Transducer Response to Thermal Transients

4.1. General Test Procedures

4.1.1. Pressure Cycling

In order to investigate the operating life of pressure transducers, an experimental technique had previously been developed by project personnel for pressure cycling these sensors[5]. Based on the experience obtained, it was thought feasible to obtain the effects of thermal transients on the zero output and full scale output of the transducers simultaneously by an adaptation of this technique. In this adaptation, the transducer is subjected to alternating pressure, while it is illuminated by the laser beam. The pressure acting on the transducer is switched rapidly and repetitively between zero gage pressure (ambient atmospheric) and the full scale value for the particular sensor under test. The transducer output was to be recorded during this entire test.

During the life testing referred to above, the pressure cycling rate was 50 cycles per minute. At this rate, pressure rise and fall times could be adjusted by means of "damping" valves to assure adequate dwell times at zero and full scale without shock exciting transducer resonances.

For the thermal transient test technique, it was thought feasible to operate at a higher cycling rate in order to achieve greater time resolution of output changes. Accordingly, experiments were performed to ascertain the optimum rate. A test transducer was mounted in the test fixture, its output displayed on an oscilloscope, and the system pressure cycled at various rates. This was done by changing the cams on the switching motor which energized the solenoid valve. It was necessary to reduce the system volume by moving the solenoid valve and the "damping" valves very close to the test fixture. Finally, they were attached directly to the fixture. After some experimentation, a switching rate of 5 hertz was achieved with a smooth rise and fall without overshoot and ringing, and with adequate dwell time at zero and full scale pressures as shown on the oscilloscope.

When we attempted to use the x-y recorder with this system, we found it unable to adequately follow this rapid cycling rate. In view of the advantages presented by the x-y recorder and considering

previously obtained thermal transient data[4], the possible higher time resolution did not seem as important as the greater amplitude resolution obtainable with this recorder. Accordingly, the cycling rate was reduced to 50 cycles per minute (0.833 hertz). The rest of the experimental work involving pressure cycling was performed at this rate.

4.1.2. Zero Pressure and Full Scale Pressure Tests

As indicated above, a small loss in time resolution may be incurred due to the restriction on the cycling rate imposed by the recorder. In addition, it proved very difficult to adjust the recorder amplifiers so that the trace showed a response without overshoot at either end, and at all amplitudes. It seemed proper, therefore, to investigate another technique. In this, the transducer is subjected first to zero gage pressure (ambient atmospheric) while the diaphragm is irradiated for a time by the laser beam and the output recorded. This is followed by a rest period of sufficient time to permit the transducer to reach ambient temperature again. Without changing any recorder setting, the full scale pressure is applied to the transducer while the diaphragm is irradiated again. Transducer output is recorded again. This technique produces two traces on one graph, showing the response at zero pressure and at full scale pressure. Differences in vertical amplitude between the two traces represent the sensitivity values throughout the test. The only requirement for validity of results is that the shutter be raised for both runs when the recording pen is at exactly the same distance from the vertical reference axis of the record.

4.1.3. Transducer Cooling

During some preliminary tests, it was noted that the zero output of the transducer, which always changes in response to the thermal transient input, did not return to its original position immediately upon beam shut-off. We decided to allow a cooling-off period before the full scale test, and to pressure cycle the transducer so as to expedite heat removal. Initially, a cooling period of five minutes was used. Subsequent tests indicated that three minutes of cooling was adequate and permitted running a larger number of tests in a given time. Since the pressure cycling panel is equipped with a mechanical counter, it was quite convenient to initiate the cycling immediately after the zero pressure test and wait an additional 150 counts (50 cycles per minute rate) had accumulated before initiating the full scale test.

4.2. Detailed Transducer Test Procedures

Three basic test procedures evolved from the preliminary experiments. Two were used in a series of short term tests, in which the transducer was exposed to the laser beam for approximately 50 seconds. They were the "zero and full scale" technique, and the "pressure cycling" technique. The third procedure involved "pressure cycling" with the laser beam turned on for about 300 seconds.

Three unbonded wire strain gage pressure transducers (three different models from two manufacturers) and one semiconductor strain gage sensor were tested. The first three were tested at four different optical power levels, using the "zero and full scale" technique first, followed by one run at the highest power level using the "pressure cycling" technique. One run using the former technique, but at half scale pressure concluded these tests (in the case of one transducer an additional run at 20% full scale was also included).

In each of these tests, the laser beam was blocked by the shutter, while the recorder was turned on to sweep at the rate of 0.5 cm per second. After 8 seconds (4 cm of trace), the shutter was raised permitting the laser beam to irradiate the transducer diaphragm for about 50 seconds, then the shutter was lowered cutting off the beam. Recording continued for about 16 more seconds until the traveling pen reached the end of the paper. When using the "zero and full scale" technique, the first run at each power level was made with zero pressure (ambient atmospheric for the "gage" pressure transducers tested). Immediately following this, the recorder was disconnected and the pressure cycling mechanism was turned on to subject the transducer to 150 pressure cycles in order to cool the diaphragm. At the conclusion of this, the transducer test fixture was pressurized to the full scale value of pressure and the recorder was reconnected without disturbing any of its settings. The recorder was then turned on and the above procedure was repeated, making sure that the shutter was raised at exactly the same time after pen motion had started, as in the previous test. This resulted in two traces separated by a distance equivalent to the full scale pressure response of the transducer.

The lowering of the shutter before the end of the record assures a qualitative check on the transducer performance by subjecting it to a "negative" thermal transient. Examination of the records indicates the corresponding transducer response to be essentially the mirror-image of its response to the positive thermal transient.

The procedure in the "pressure cycling" technique subjects the transducer alternately to zero and full scale pressure at the rate of 0.833 Hz before, during and after laser beam irradiation of the diaphragm. Recording speed and shutter operation is the same as it is for the other techniques described above.

Finally the third technique is simply an extended time version of the "pressure cycling" technique, with the diaphragm exposed to the laser beam for about 320 seconds. The recording speed in this case is 0.1cm/s.

In all tests, the transducer was mounted in a brass plug with the diaphragm flush with the front face of the plug. In a short series of final tests, the transducer was mounted in a plug made of polytetrafluoroethylene, a plastic material of low thermal conductivity, to assess the effects of the heat conductivity of the mounting.

4.3. Transducer Test Results

4.3.1. Data Reduction Considerations

The data obtained from the tests were in the form of curves recorded on 28 cm x 42 cm (11 x 16-1/2 in.) sheets of graph paper. The results of the tests were obtained from these recordings by scaling certain distances at specified locations. Figure 11, "Data Reduction Points for Thermal Transient Tests", shows this in detail. The curves shown in Figure 11 are typical of many transducers and the principles illustrated can readily be applied to other transducers. Distance "A", the difference between zero pressure and full scale pressure, represents the transducer's sensitivity before the laser beam is turned on. "B" represents the negative excursion due, most likely, to the heat induced expansion of the pre-loaded diaphragm. This is found in most transducers tested. "C" is the zero shift (referred to the initial zero pressure output) 20 seconds after the transducer was first exposed to the laser beam. This time interval was chosen on the basis of preliminary experiments which indicated that most of the change in transducer characteristics due to laser irradiation has occurred by that time. "D" is the change in full scale output at the same time, and "E" represents the new sensitivity after 20 seconds of irradiation. Similarly, "F", "G", and "H" are the corresponding characteristics 40 seconds after beam turn-on. This time was chosen not only as a simple multiple of the 20 second period, but also as one close to the end of the test.

For the long term test an additional set of data was read from the record at a time 300 seconds after the laser beam was turned on. Values are designated as F^1, G^1, H^1 in Table IV.

4.3.2. Results from Short Term Tests

The data from the short term tests (laser beam on for about 50 seconds) are shown in Figures 12 - 16. Figure 12 shows the response of an unbonded wire strain gage pressure transducer at four different optical power levels. In each case, there is an initial dip in the response (in the direction of a negative-going pressure). We believe this is due to the outward expansion of the pre-loaded diaphragm caused by the sudden input of thermal energy. This is almost immediately (within about 4 seconds) overtaken by the positive going response. This response flattens out within about 40 seconds and remains at this level until the end of the test when the shutter is closed. Upon shutter closure, the transducer's reaction shows almost the mirror image of its response to shutter opening. This was true for all transducers tested. Tests of this transducer at the four power levels show responses very similar in appearance, with parameter changes roughly proportional to the power levels, as can be seen from the data in Table II and also in Figure 16. In this table the test results are compiled for the data reduction characteristics illustrated in Figure 11. All results are presented in terms of a percentage of the full scale range of the transducer before its exposure to the thermal transient. This is represented by the

distance "A" in Figure 11. "E" and "H" represent the full scale range 20 and 40 seconds, respectively, after the beginning of the thermal transient. Numerical changes in the full scale range due to the thermal transient (increases in all cases) were computed by dividing those test values like "E" or "H" by "A", subtracting 1.00 from these ratios and converting to a percentage. Since the full scale range divided by the applied pressure is the transducer's sensitivity, the tabular values reported under "$\Delta\frac{E}{A}$" and "$\Delta\frac{H}{A}$" show percentage changes in sensitivity due to the effects of thermal transients in all tables in this paper.

TABLE II

Results of Short Term
"Zero and Full Scale" Thermal Transient Testing Technique

Refer to Figure 11 For Explanation of Characteristics

Transducer	Optical Power Watts	Characteristic in % Full Scale Range "A"						
		B	C	D	$\Delta\frac{E}{A}$	F	G	$\Delta\frac{H}{A}$
A	2.1	-3.5	+9.9	+13.8	+3.8	+11.9	+15.4	+3.9
	5.2	-8.7	+16.7	+27.2	+10.2	+20.8	+30.5	+10.7
	8.4	-13.8	+18.6	+32.1	+13.5	+23.8	+36.8	+13.1
	12.4	-17.5	+22.9	+39.2	+17.5	+27.7	+44.7	+17.3
B	2.1	-0.9	+4.4	+7.1	+2.5	+4.7	+7.7	+2.9
	5.2	-1.9	+6.5	+12.7	+6.5	+7.2	+13.9	+6.6
	8.4	-3.7	+6.2	+14.7	+8.5	+7.4	+15.9	+8.7
	12.5	-5.0	+5.6	+15.8	+10.2	+7.2	+17.7	+10.2
C	2.1	-2.4	-1.1	+5.5	+6.6	-0.8	+5.7	+6.2
	5.2	-5.0	-3.3	+10.7	+14.0	-2.6	+11.5	+14.5
	8.4	-5.7	-5.2	+12.2	+17.1	-4.1	+13.7	+17.6
	12.4	-7.2	-7.8	+13.4	+21.4	-6.1	+15.1	+21.7
D	0.15	--	45	33	-12	--	--	--

Figure 13 shows test results at the highest optical power level, using the same "zero and full scale" technique for the four transducers tested. It can be seen that each of these four transducers responds in a different manner to the same thermal transient input. It is interesting to note that the three transducers whose responses are shown in Figure 13 (A, B, C) are all unbonded wire strain gage types with a range of 50 psi. The fourth (D) is a semiconductor sensor with the strain gage diffused into a silicon diaphragm and a range of 5 psi.

The unexpectedly large response of the latter even at a very low power level (0.15 watts, about 1.2% of the power level used for the other three) strongly suggests that such semiconductor sensors should be used with great caution in thermal transient environments.

Figure 14 shows the results from tests at the highest optical power level, using the "pressure cycling" technique on the same four transducers. The characteristics obtained from the records are compiled in Table III, which also repeats those values from the tests at the same power level from Table II to enable a ready comparison. In addition the table shows the data obtained when the transducer was mounted in a polytetrafluroethylene retainer instead of the brass plug used for most tests. Figure 15 shows graphically the data obtained from these comparison tests. Figure 16 shows the results from tests on three of the transducers which are contained in Table II, including tests with the transducer mounted in the non-conducting retainer.

4.3.2.1. "Zero and Full Scale" Technique

Data plotted in Figure 16, and obtained from short term tests using the "zero and full scale" technique, show the maximum initial negative excursion of the diaphragm, the position of the zero trace 20 seconds after shutter opening, and the sensitivity at the same time. It can be seen that all but one plot shows effects which increase in magnitude with power level in a fairly linear manner. Secondly, with one exception, the data obtained with the non-conducting transducer mounting are quite close to those with the brass plug.

The magnitudes of the transient thermal effects seem large. At an optical power level of 12.5 watts on a 1/2 in. diameter diaphragm the power density is 10 W/cm^2 [8.7 $(Btu/ft^2)/$ or 0.06 $(Btu/in^2)/s$. It is reported that energy transfer rates in rocket engines range from 0.5 $(Btu/in^2)/s$ to as much as 25 $(Btu/in^2)/s$, (83 W/cm^2 to 4170 W/cm^2)[6]. Thus, during our tests at the maximum optical power levels, the transducers were exposed to radiant power levels ranging from about 12% down to 0.3% of what they might encounter in a rocket chamber environment. Yet our optical power test level resulted in zero shifts ranging from 13.4% to 39.2% of full scale and sensitivity increases from 10.2% to 21.4% of full scale for the three unbonded strain gage transducers. As the diaphragm temperature increases, its stiffness lessens, resulting in increased sensitivity. For the semiconductor strain gage transducer, the power density was 4.0 W/cm^2. This required an optical power level of

only 0.15 watts due to the fact that the diaphragm diameter of this transducer (D) is only 0.085 in. (0.22 cm). This power density resulted in a zero shift of 45% FS and a sensitivity shift of about -12%. A large amount of noise was observed during tests on the latter transducer. Much of this is believed to be due to the photoelectric response of this transducer. This was checked by repeating the thermal transient test without any electrical excitation of the transducer. Results indicated a photoelectric sensitivity ranging from about 0.15 mV/(W/cm^2) to 0.30 mV/(W/cm^2). Referred to this transducer's pressure sensitivity, this amounts to an equivalent output of about 0.01 to 0.02 psi/ (W/cm^2) for this 5 psi range transducer.

Results compiled in Table II also show only insignificant additional changes in sensitivity 40 seconds after shutter closing (column "$\Delta\frac{H}{A}$"), compared to values at 20 seconds (column "$\Delta\frac{E}{A}$"), and relatively small additional changes in zero output (columns "C" and "F").

This indicates that the diaphragm temperature apparently stabilizes within the first 20 seconds, while thermal gradients within the body of the transducer do not become stabilized until about 40 seconds have elapsed. After this period, the thermal gradient does not change and the resultant zero pressure output remains constant.

The diaphragm of a previously disassembled transducer quite similar in size and design to Transducer A was instrumented with a small thermocouple pressed into a boss on the center inside surface of the diaphragm. This assembly was also exposed to various levels of optical power, and the thermocouple output recorded. The measurement showed the expected exponential response with a time constant of about 4 seconds. The maximum diaphragm temperature measured at an optical power level of 12.5 watts was 190°F (88°C). One can probably assume that the actual diaphragm temperature during a test is a little higher than this, since some heat is undoubtedly conducted away by the thermocouple itself. We believe, however, that the diaphragm temperature did not exceed the operating limit of 250°F (121°C) for the transducer with the lowest limit. Unbonded straingage transducers such as the ones tested typically carry specifications for zero shift and sensitivity change of 2%/100°F temperature change. Assuming a temperature change of 180°F (82°C) from ambient to 250°F, one would expect the two characteristics to change by about 3.6%. The smallest changes observed during the tests, however, were 13.4% for zero shift and 10.2% for sensitivity shift.

4.3.2.2. "Pressure Cycling" Technique

The "pressure cycling" technique was used only at the highest optical power level. The results of the tests in Table III below show clearly that only very small numerical differences were observed in zero shift and sensitivity change for this method, as compared to the "zero and full scale" technique, data from which are plotted in Figure 16.
It does appear, however, that the values obtained from the cycling tests are slightly smaller numerically than those from the other method. We believe this to be due to the cooling effect of the air circulation

during cycling. For comparison, data taken with the transducer in the non-conducting mounting at the same power level show also substantially the same values. The disagreement between values of sensitivity change observed for the semiconductor device is attributed to the large noise level present due to photoelectric effects which introduces larger uncertainties into the data reduction.

TABLE III

Results of Short Term
"Pressure Cycling" Thermal Transient Testing Technique

Refer to Figure 11 for Explanation of Characteristics

Characteristic in % Full Scale Range "A"

Transducer	Mount	Method	Optical Power Watts	B	C	D	$\Delta\frac{E}{A}$	F	G	$\Delta\frac{H}{A}$
A	Brass	cycling	12.4	-18.1	+22.3	+37.4	+16.0	+27.8	+43.4	+16.1
	Brass	zero+FS	12.4	-17.5	+22.9	+39.2	+17.5	+27.7	+44.7	+17.3
	Plastic*	cycling	12.3	-15.6	+34.9	+49.6	+15.6	+52.2	+65.3	+15.6
B	Brass	cycling	12.5	-4.4	+4.7	+15.0	+10.3	+6.3	+16.7	+10.3
	Brass	zero+FS	12.5	-5.0	+5.6	+15.8	+10.2	+7.2	+17.7	+10.2
	Plastic*	cycling	12.0	-3.5	+3.0	+13.6	+10.1	+4.1	+14.1	+10.1
C	Brass	cycling	12.4	-6.9	-7.4	+13.2	+21.1	-5.6	+14.8	+21.4
	Brass	zero+FS	12.4	-7.2	-7.8	+13.4	+21.4	-6.1	+15.1	+21.7
	Plastic*	cycling	12.0	-7.4	-7.7	+10.9	+18.7	-7.4	+11.4	+19.3
D	Brass	cycling	0.15	--	+47	+48	+1.0	--	--	--
	Brass	zero+FS	0.15	--	+45	+33	-12	--	--	--

*Polytetrafluoroethylene

4.3.3. Results from Long Term Tests

Figure 17 shows the results from the "long term" tests, in which the transducer diaphragm was exposed to the laser beam for a little more than 300 seconds. For these tests, the "pressure cycling" technique was used. The results from these tests are compiled in Table IV below. The data reduction points in this case were the same ones shown in Figure 11, with an additional set of points 300 seconds after shutter opening, F^1, G^1, H^1, corresponding to F, G, and H, respectively. In this series of tests, a bonded wire strain gage transducer was included, transducer E.

There appears to be relatively little change in zero output or sensitivity between the 40 second point and the 300 second point. This suggests that for transducers such as these, without auxiliary cooling or shielded diaphragms, a test duration of the order of one minute should be adequate.

Some differences were observed between these data and those obtained previously during the short term tests. All values obtained from the long term tests are an average of 13% lower. We attribute this primarily to the fact that the actual optical power level used for these tests was less by an estimated 10% caused by the use of another absorption head, whose calibration factor was subsequently found to be about 10% lower than that of the absorption head used for the previous tests.

This time the semiconductor transducer was tested at the full power level, and a bonded strain gage transducer was also included. The former exhibited zero shift and sensitivity change of 381% and -11% FS, respectively, while the latter showed changes of 113% and 7.9%, respectively. This zero shift is considerably greater than for the unbonded strain gage transducers also tested.

TABLE IV

Results of Long Term
"Pressure Cycling" Thermal Transient Testing Technique

Refer to Figure 11 for Explanation of Characteristics

Transducer	Optical Power Watts	B	C	D	$\Delta\frac{E}{A}$	F	G	$\Delta\frac{H}{A}$
		Characteristics in % Full Scale Range "A"						
A	12.3	+16.8	+19.6	+33.5	+13.4	+24.6	+39.1	+13.9
B	12.3	-3.4	+4.3	+14.6	+9.9	+6.0	+16.3	+9.9
C	12.3	-7.0	-6.3	+12.5	+18.4	-5.1	+14.5	+19.1
D	12.3	--	+381	+384	-11	+383	+389	-11
E	12.3	--	+113	+121	+7.9	+115	+124	+7.9

Transducer	Optical Power Watts		F^1	G^1	$\Delta\frac{H}{A}$
A	12.3		+24.6	+38.5	+13.9
B	12.3		+6.6	+16.7	+9.9
C	12.3		-4.7	+14.9	+19.1
D	12.3		+409	+395	-11
E	12.3		+113	+121	+7.3

4.3.4. Results from Tests at Pressures Less Than Full Scale Range

During the "zero and full scale" short term series of tests, some additional tests were run on the three unbonded strain gage test transducers. In these tests, performed at the maximum optical power level of about 12.4 watts, each transducer was pressurized to 50% of its full scale range, and in one case to only 20% of the range. The test results are shown in Table V, along with results from the full scale tests at the same optical power level. It can readily be seen that there are no significant differences between values of zero shift (both initial negative shift "B", and subsequent shifts "C" and "F") and sensitivity changes between previous tests at the full scale pressure range and the tests at pressures less than full scale range. The zero shifts in Table V were computed from the data, as in all previous tests, by dividing the measured trace shift by the displacement corresponding to the full scale range and converting to a percentage of the full scale range. Sensitivity shifts were computed, as before by measuring the distance between the zero and test pressure traces on the record after 20 and 40 seconds, dividing these quantities by the displacement corresponding to the test pressure and converting this ratio to a percentage change shown as "$\Delta\frac{E}{A}$". For a linear transducer the percentage change in sensitivity for the same thermal transient stimulus should be same regardless of the pressure level. This is borne out by the data in Table V. The changes at the full test pressure, "D" or "G", are due to the combination of the zero shifts "C" or "F" and the changes in sensitivity "$\Delta\frac{E}{A}$" or "$\Delta\frac{H}{A}$". The table shows good agreement for this for the tests at the full scale range. At 50% of the full scale range, the contribution of the change in sensitivity to the magnitude of the changes at "D" or "G" should only be 50% of that found during tests at 100% FSR. When these lower values are combined with the observed values of zero shift (which are independent of test pressure), reasonable agreement exists in most cases. One can cite as an example from Table V for transducer A at 100% FSR, "D" (+39.2%) should equal "$\Delta\frac{E}{A}$" (+17.5%) plus "C" (22.9%); the actual sum is +40.4%. At the 50% FSR level, "D" (30.2%) should equal "$\Delta\frac{E}{A}$" divided by 2 (50% FSR) ($+\frac{16.0}{2}$%) plus "C" (21.9%); the actual sum is 29.9% for the same transducer.

TABLE V

Results of Short Term Tests at Pressures Less Than Full Scale Values Compared to "Zero and Full Scale" Test Values

Refer to Figure 11 for Explanation of Characteristics

Transducer	Optical Power Watts	Test Pressure Range % FS	Characteristic in % Full Scale Range "A"						
			B	C	D	$\Delta\frac{E}{A}$	F	G	$\Delta\frac{H}{A}$
A	12.4	50	-18.5	+21.9	+30.2	+16.0	+27.8	+36.8	+17.3
	12.4	100	-17.5	+22.9	+39.2	+17.5	+27.7	+44.7	+17.3
B	12.5	50	-4.6	+5.2	+10.3	+10.4	+6.7	+12.0	+11.1
	12.5	100	-5.0	+5.6	+15.8	+10.2	+7.2	+17.7	+10.2
C	12.4	20	-7.0	-7.1	- 2.5	+22.9	-5.8	-0.8	+24.4
	12.4	50	-7.1	-7.1	+4.6	+23.6	-5.6	+6.3	+24.4
	12.4	100	-7.2	-7.8	+13.4	+21.4	-6.1	+15.5	+21.7

The results from these tests suggest the feasibility of testing transducers at less than their full scale pressure range for zero shifts and sensitivity changes due to thermal transients. Thus, the present test and setup, originally designed for an operating pressure of 8.6 x 10^5 N/m^2 (125 psi) (limited by the glass window and solenoid valves) appears quite suitable for testing transducers with full scale ranges up to 34.5 x 10^5 N/m^2 (500 psi).

5. Conclusions

5.1. Test Methods

The results obtained from all tests indicate that a simple, practical, and repeatable test technique is now available for determining the effects of thermal transients on flush diaphragm pressure transducers. The tests also indicate that both methods, "zero and full scale" and "pressure cycling" appear equally suitable for obtaining the desired data. The "zero and full scale" procedure permits slightly greater time and amplitude resolution, but requires greater care in synchronizing shutter operation and in assurance of low amplifier drift. The "pressure cycling" procedure requires less care in timing and presents an impressive

demonstration of thermal transient effects in about half the testing time required for the other procedures.

Test results also indicate that it sould be possible to adequately assess transducer performance when testing at less than the full scale pressure range of the transducer. Consequently it should be possible to test transducers with ranges up to 34.5 N/m^2 (500 psi) with the use of this technique originally designed for a maximum pressure of 8.6 x 10^5 N/m^2 (125 psi).

Finally, it appears that a testing time of about one minute is adequate to establish the thermal transient response of flush diaphragm transducers of the type investigated.

5.2. Test Results

Test data indicate substantial changes in zero pressure output and sensitivity when a flush diaphragm pressure transducer is subjected to a thermal transient. In all cases, a negative going shift in output signal (caused by the outward expansion of the preloaded diaphragm), stabilized after 20 to 40 seconds and remained at this value for at least the next 260 seconds. Similarly the sensitivity increased in all but one case (the semiconductor strain gage transducer). Again, this increase reached a stable value about 20 seconds after thermal exposure.

Although precise temperature data are not available, it appears that changes in zero output and sensitivity due to the thermal transient were much greater than those predictable from the manufacturer's specified steady state temperature characteristics. It appears very difficult, if not impossible, to predict a transducer's thermal transient response from its design features. Hence the value of such a simple, repeatable testing technique.

Finally, the thermal conductivity of the transducer mounting does not seem to affect its thermal transient response characteristics significantly.

6. Recommendations

Further work is required in this area, since many pressure transducers are currently used in thermal transient environments with little user awareness of the resultant potentially large measurement errors. We believe that a number of additional investigations should be undertaken using this simple, repeatable and realistic thermal transient testing technique.

A broad range sampling of commercially available flush diaphragm pressure transducers should be undertaken. This sampling should include different sensing principles, pressure ranges and sizes. Particular care should be devoted to rests of semiconductor strain gage devices.

Tests should be performed on some cavity-type pressure transducers to assess the effectiveness of this technique for this class of devices. Tests should be performed on transducers with artificial cooling or temperature isolation provisions. This may require modification of the laser setup to attain higher power levels at the sensor.

Tests of various diaphragm coating schemes designed to reduce or delay thermal transient effects could easily be performed with this technique. These tests must be combined with dynamic pressure calibrations to assess the effect of diaphragm coatings on the dynamic response of the transducers.

We believe the continuation of our work, as outlined, using this newly developed thermal transient testing technique will contribute very significantly to meaningful, economic pressure measurement in the presence of thermal transients.

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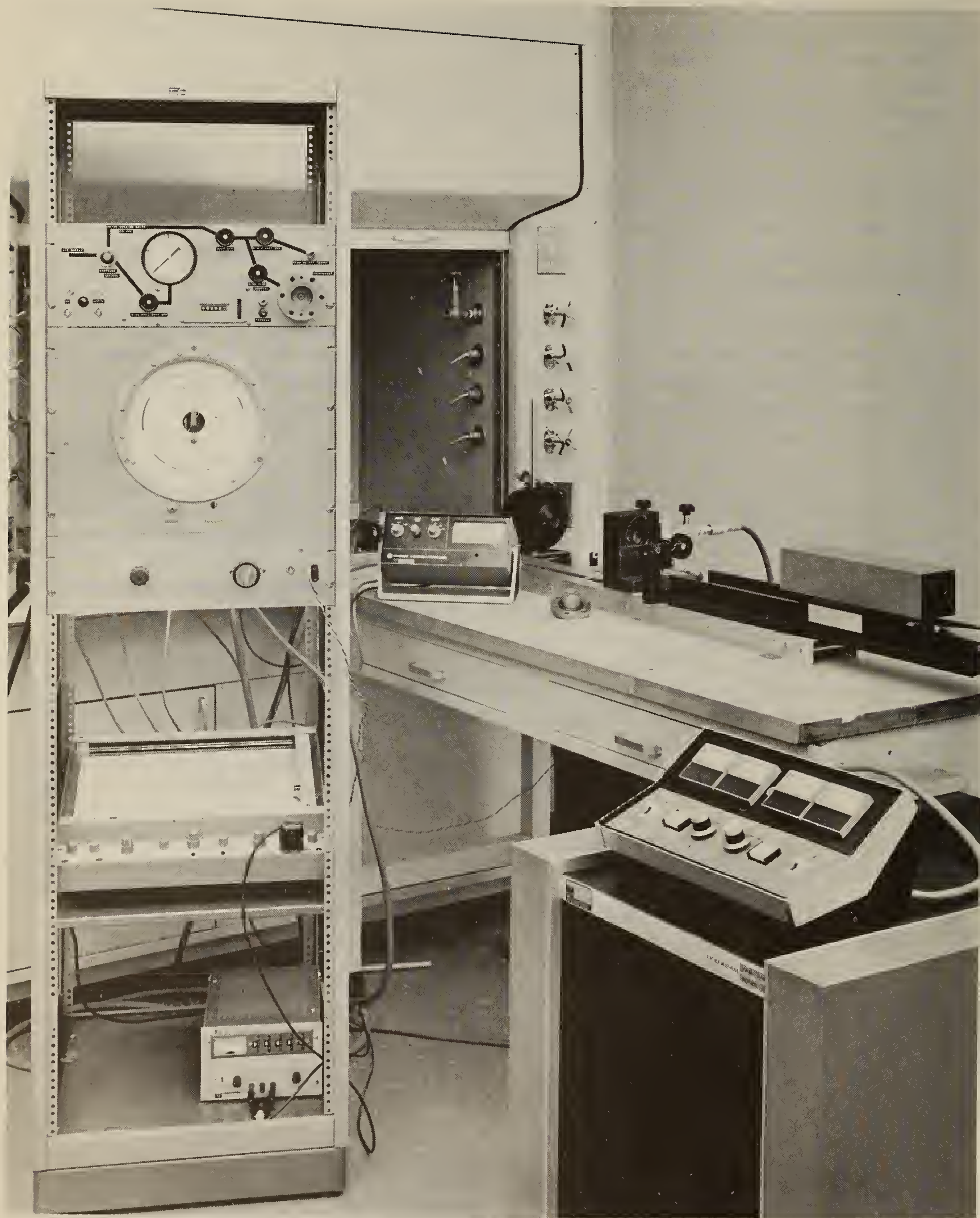


FIGURE 1. Experimental setup for laser thermal transient tests on pressure transducers.

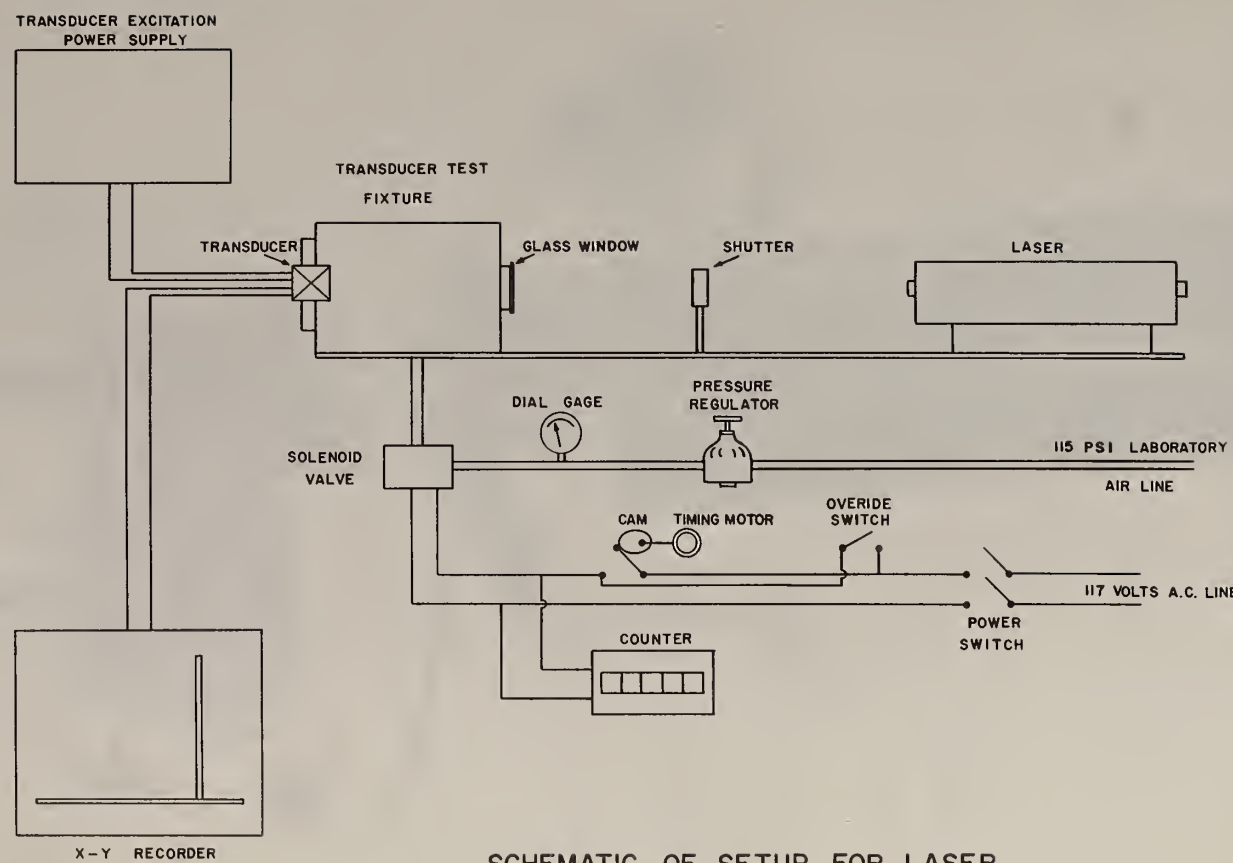


FIGURE 2 SCHEMATIC OF SETUP FOR LASER THERMAL TRANSIENT TESTER

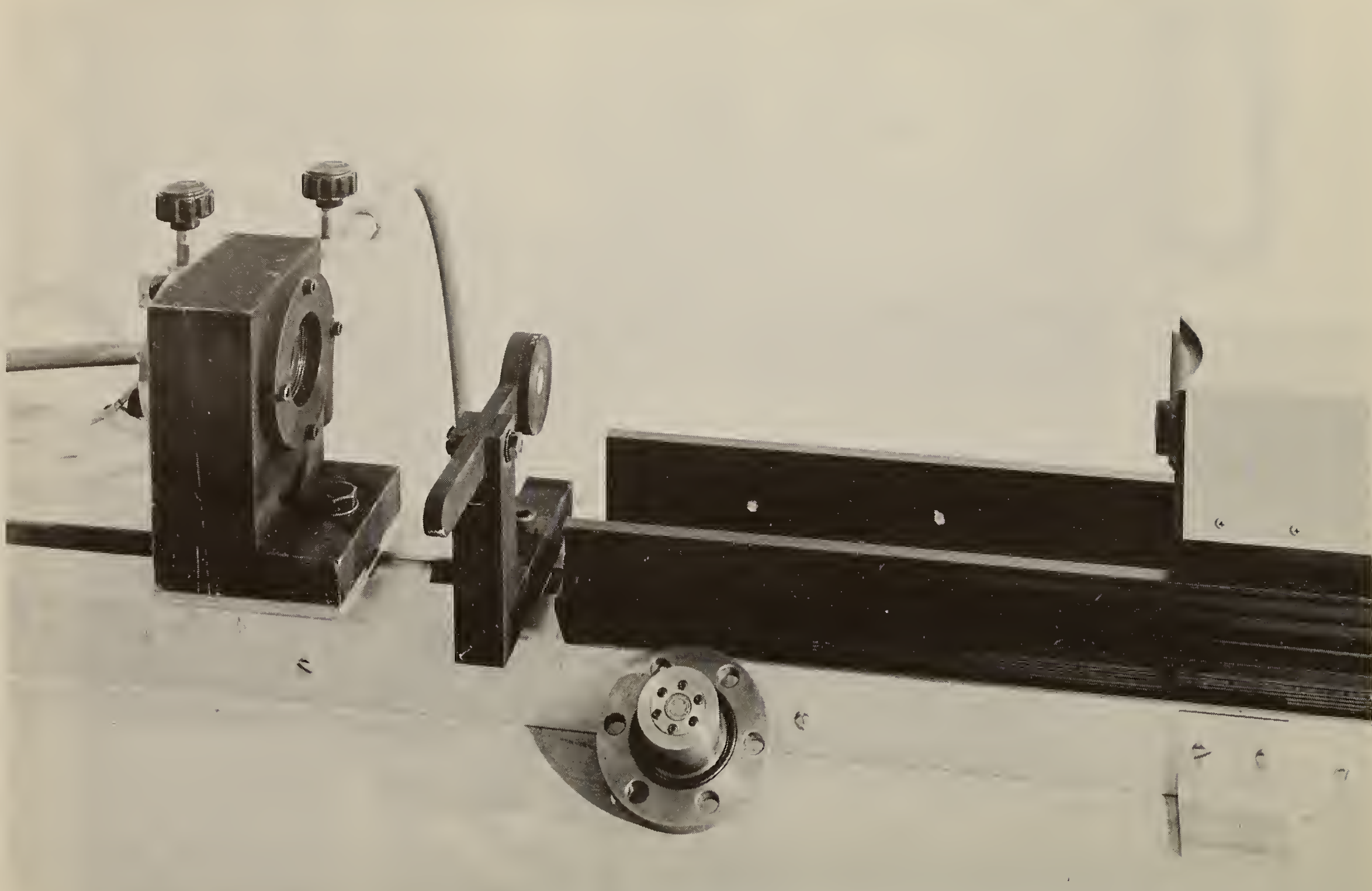


FIGURE 3. View of transducer test fixture, shutter assembly, and laser head.

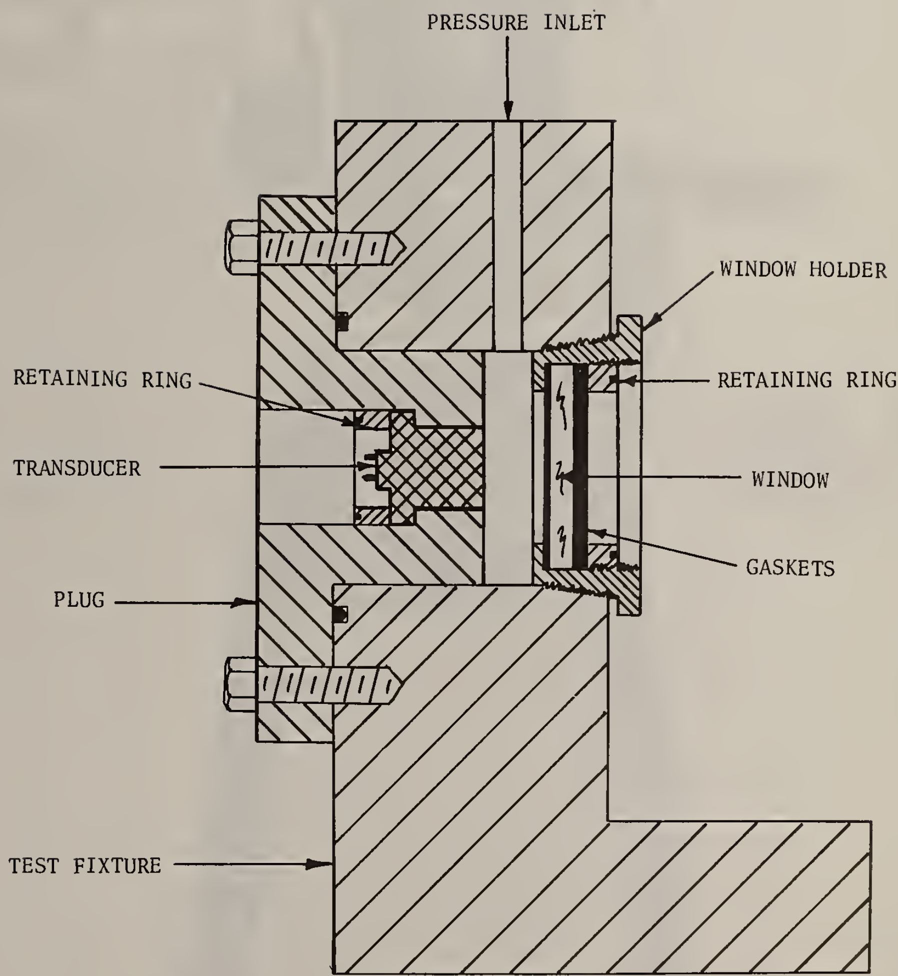


FIGURE 4. Cross section view of transducer test fixture.

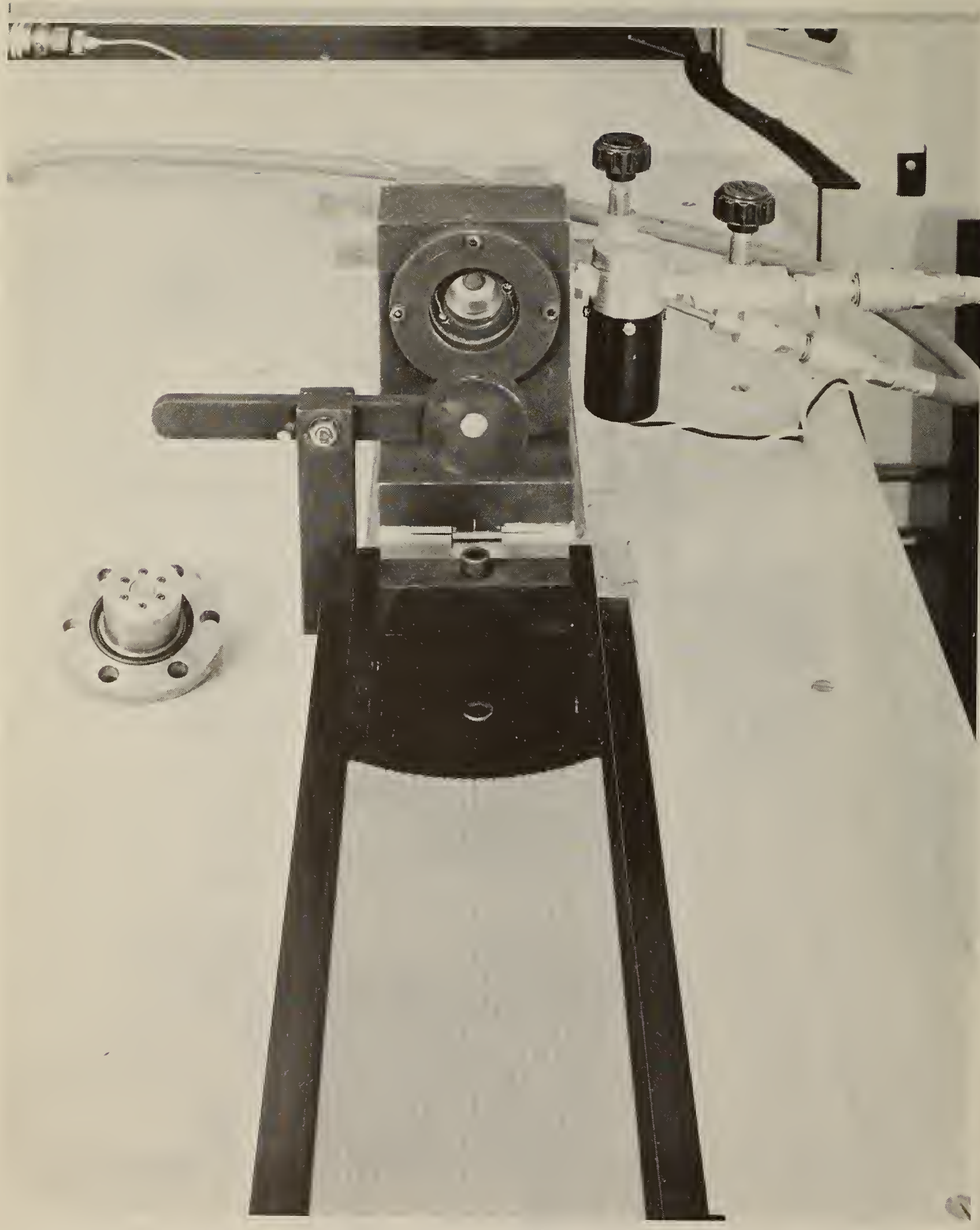


FIGURE 5. Head-on view of transducer test fixture, showing transducer diaphragm.

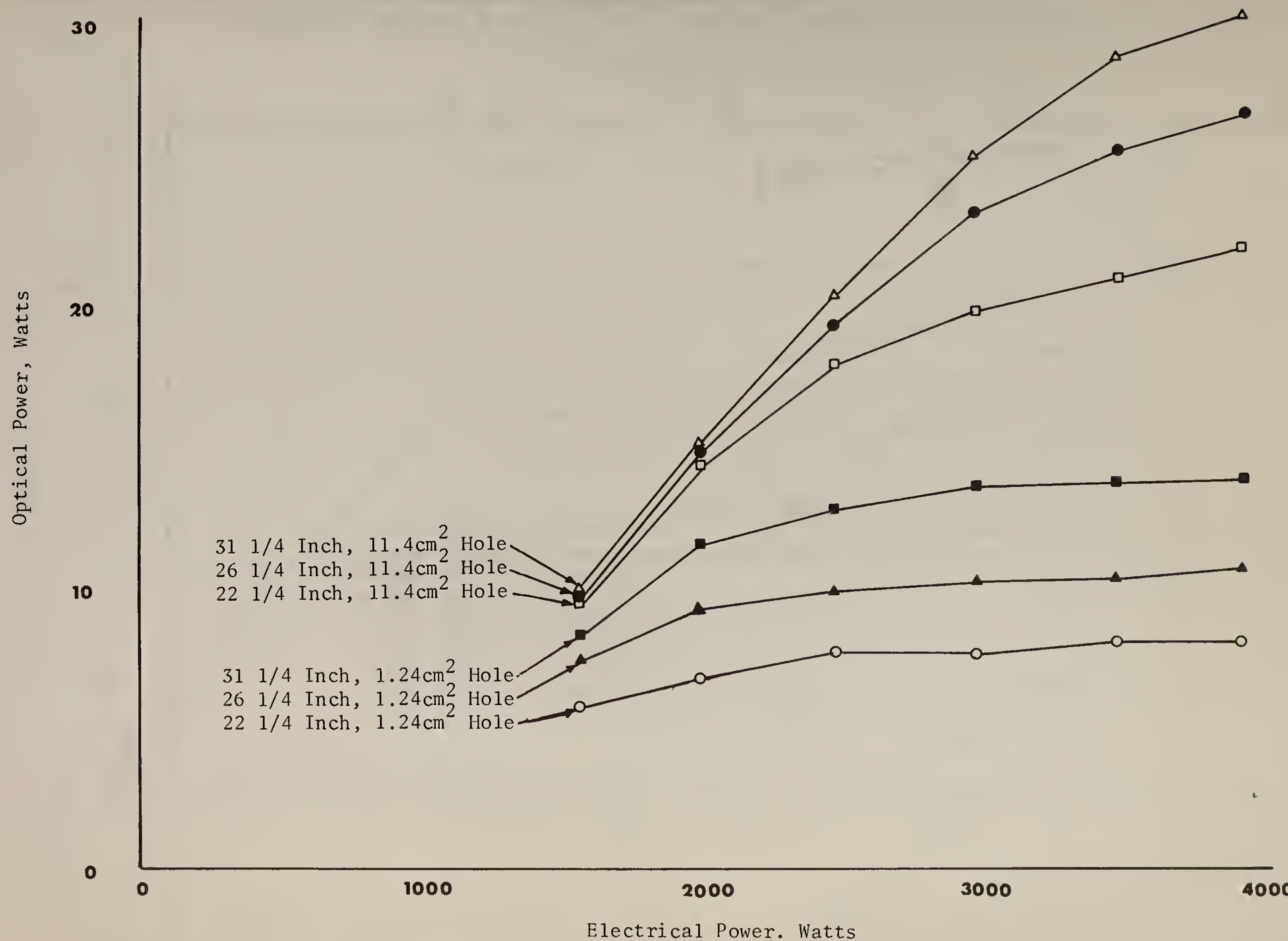


FIGURE 6. Optical power of laser beam as a function of electrical power at various distances.

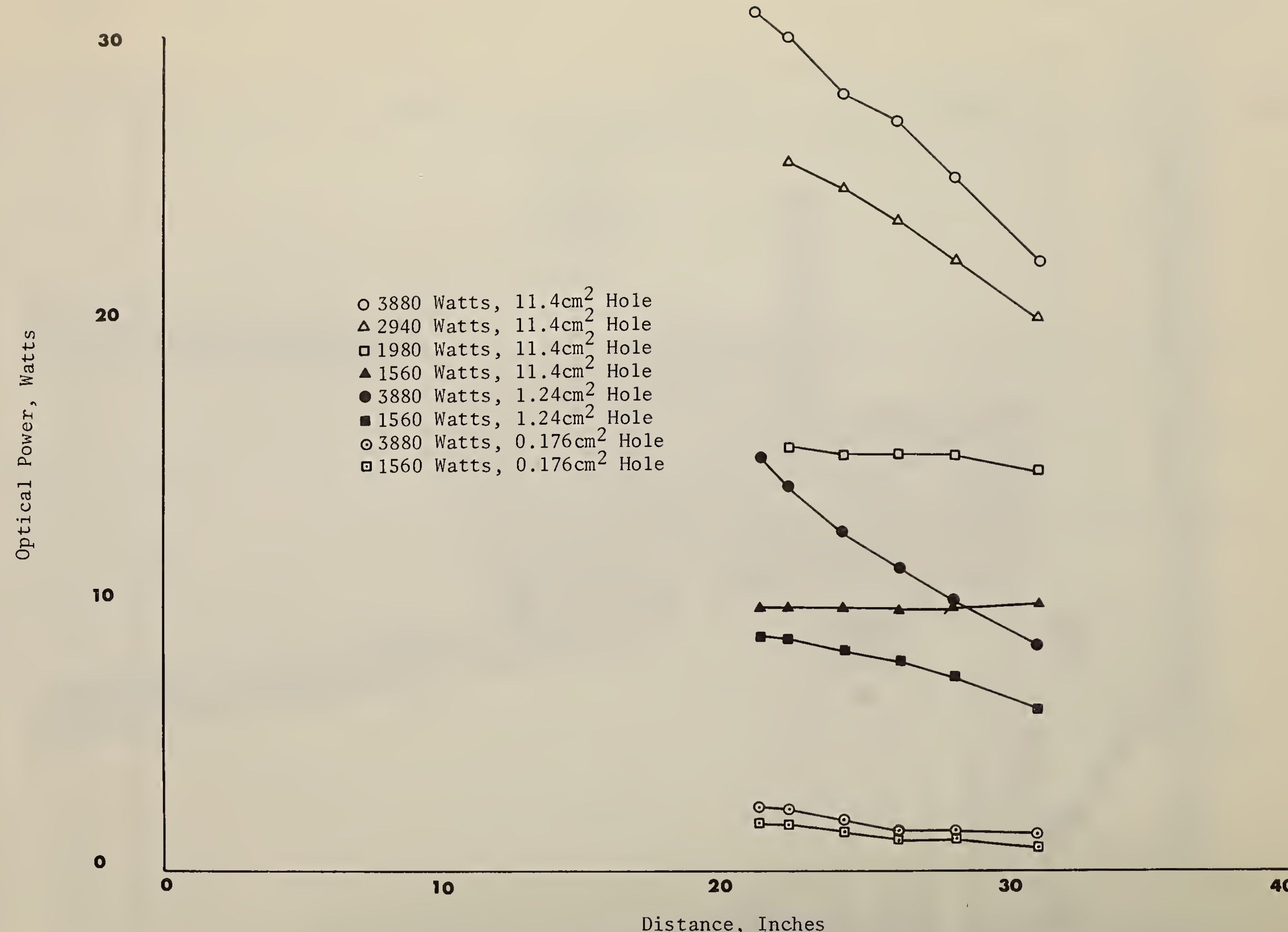


FIGURE 7. Optical power of laser beam as a function of distance at various electrical power levels.

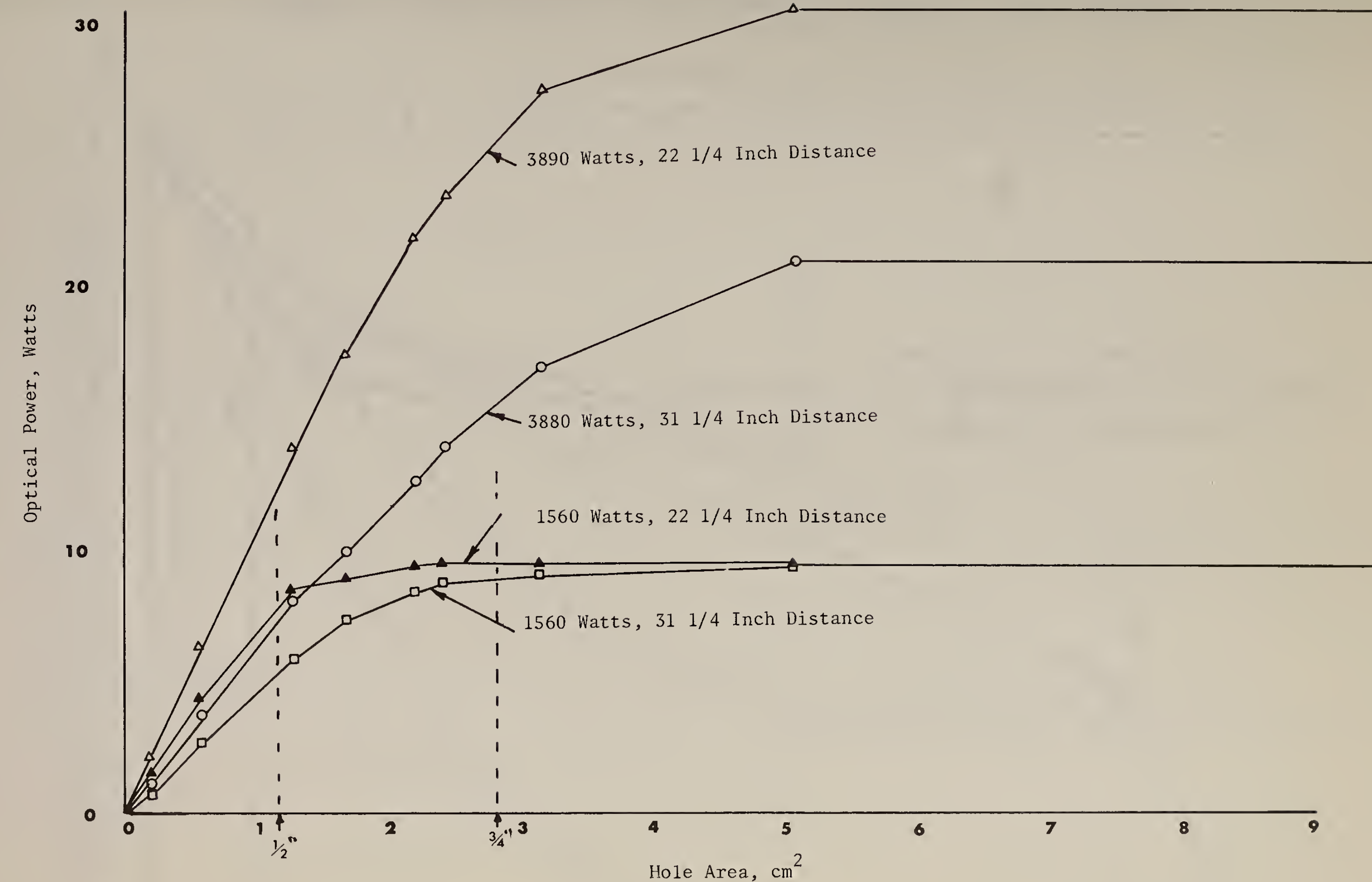


FIGURE 8. Optical power of laser beam as a function of test fixture hole area (with glass window).

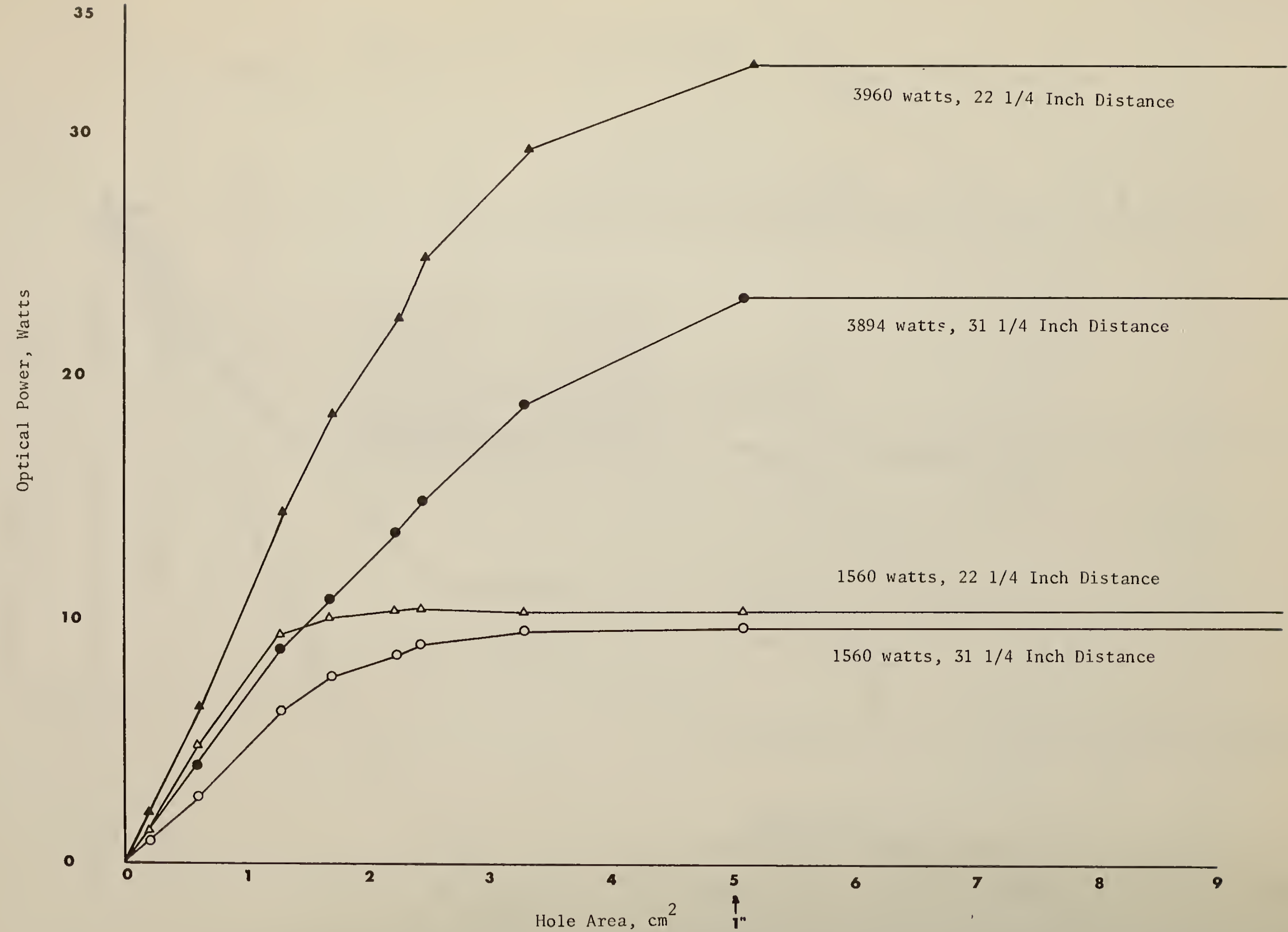


FIGURE 9. Optical power of laser beam as a function of test fixture hole area (without glass window).

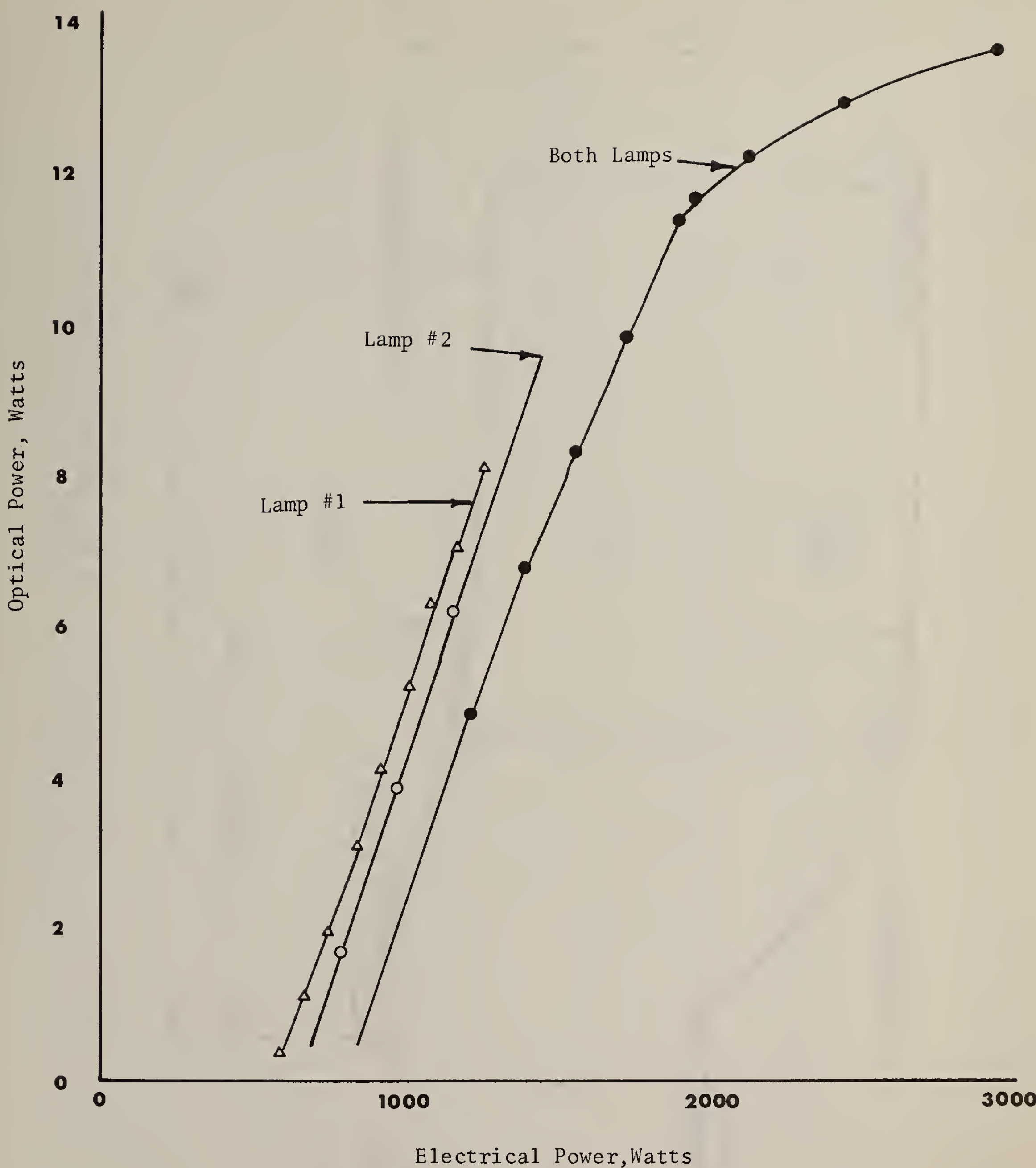


FIGURE 10. Optical power as a function of electrical power with test hole area of 1.24 cm^2 for various lamp combinations.

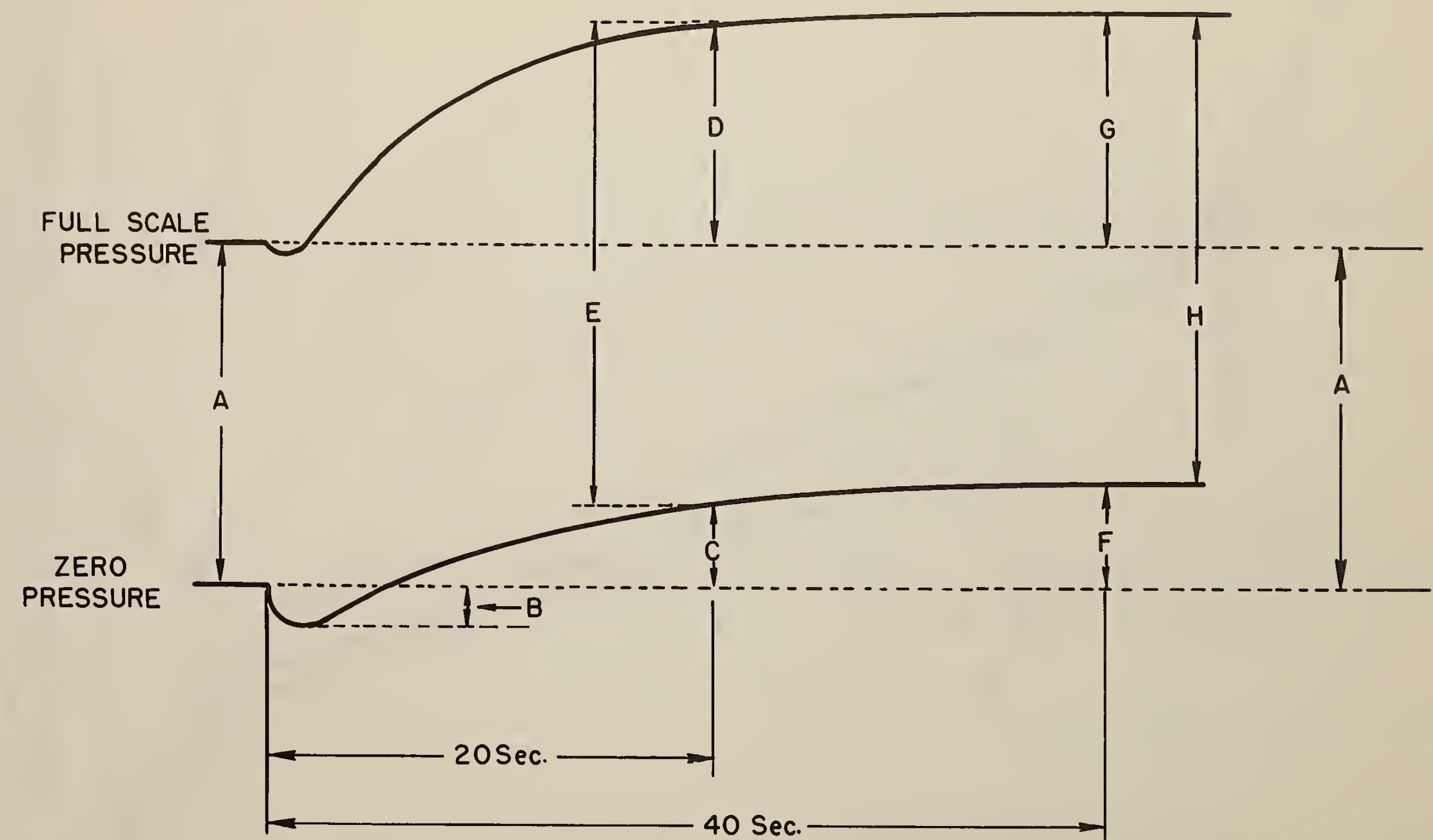


FIGURE 11. Data reduction points for thermal transient tests.

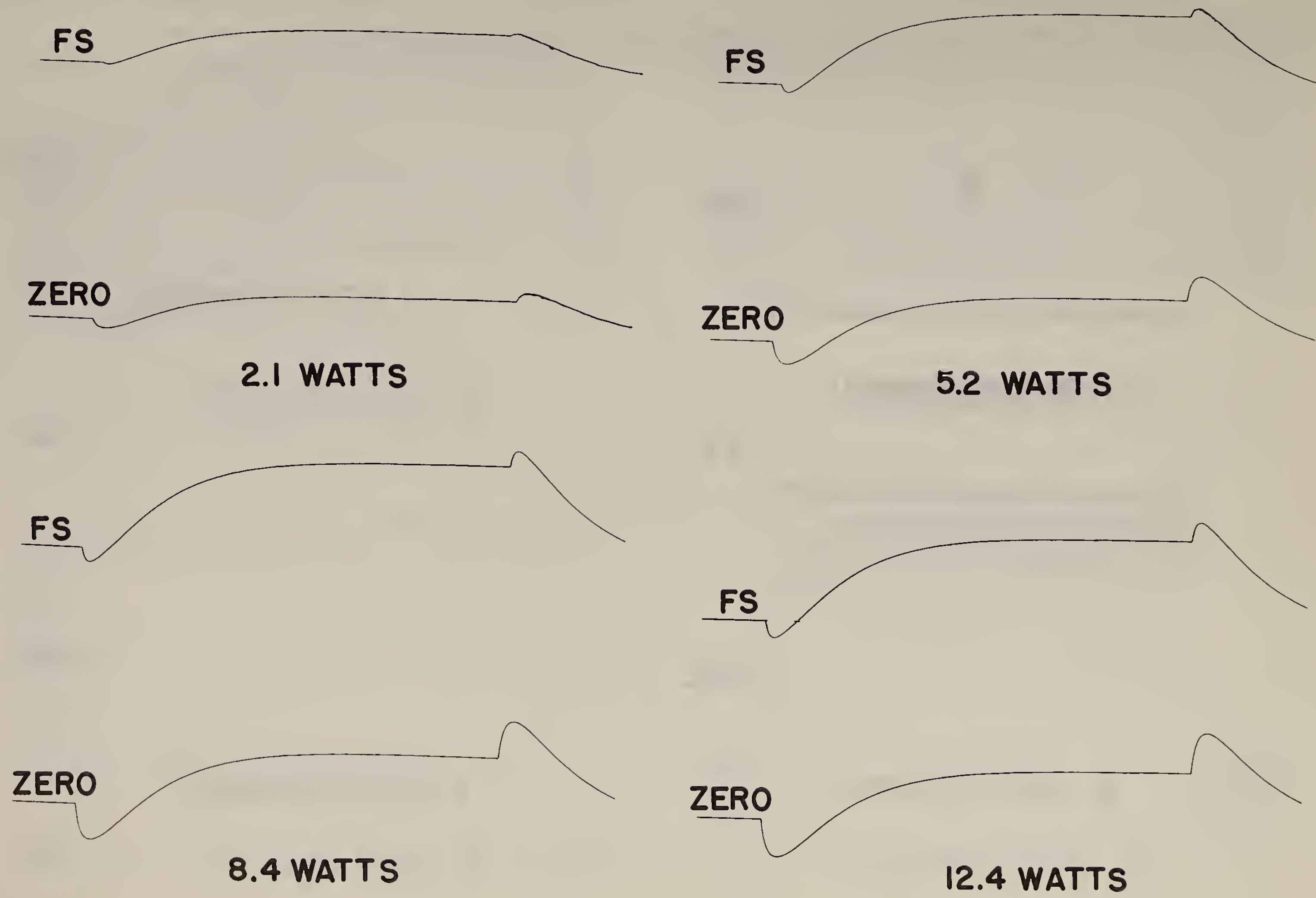


FIGURE 12. Thermal transient responses of unbonded wire strain gage pressure transducer A, "zero and full scale technique", short term tests, at four power levels.

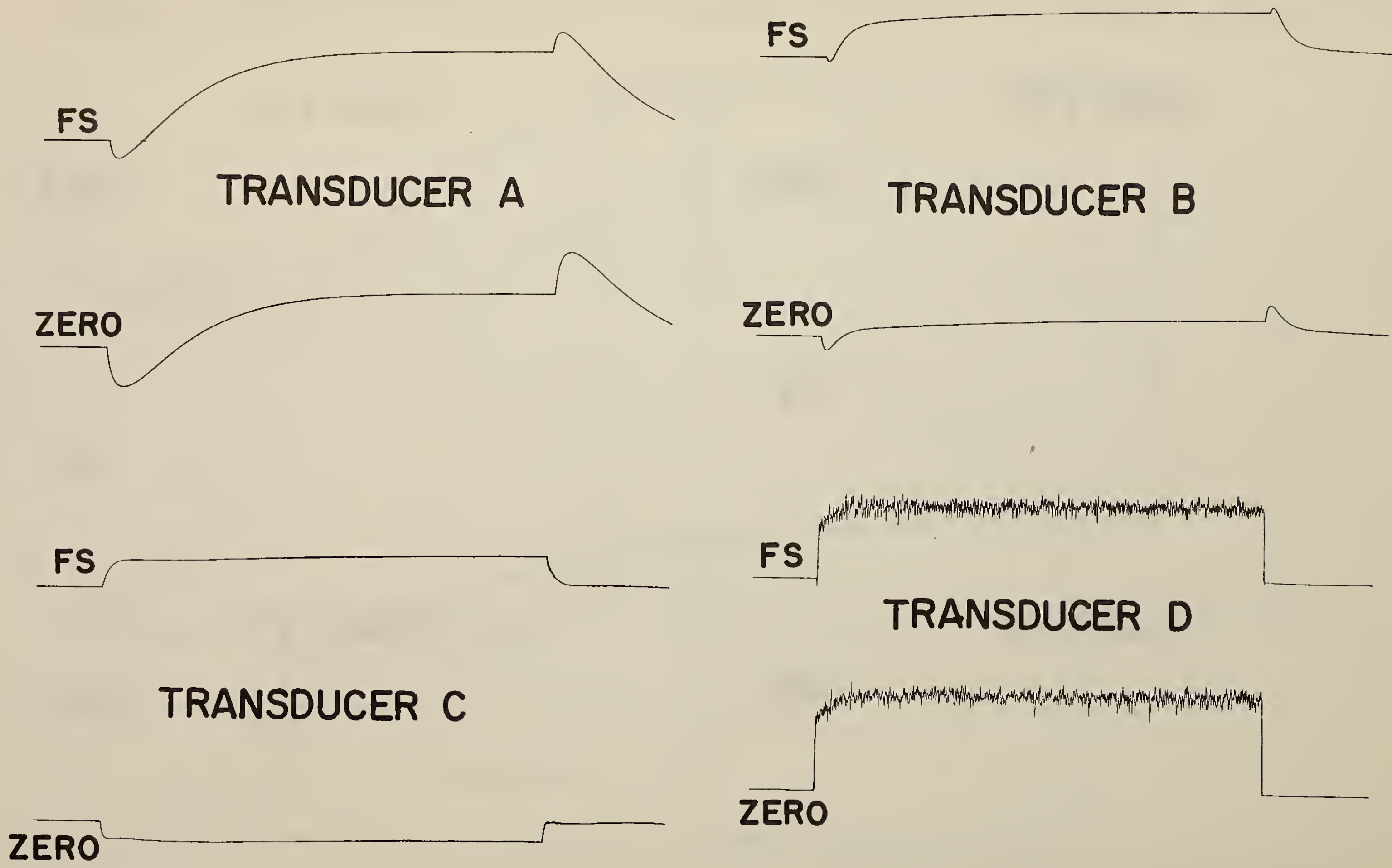


FIGURE 13 Thermal transient responses of four flush diaphragm pressure transducers: (A,B,C) at about 12.4 watts, (D) at about 0.15 watts. "Zero and full scale technique", short term tests

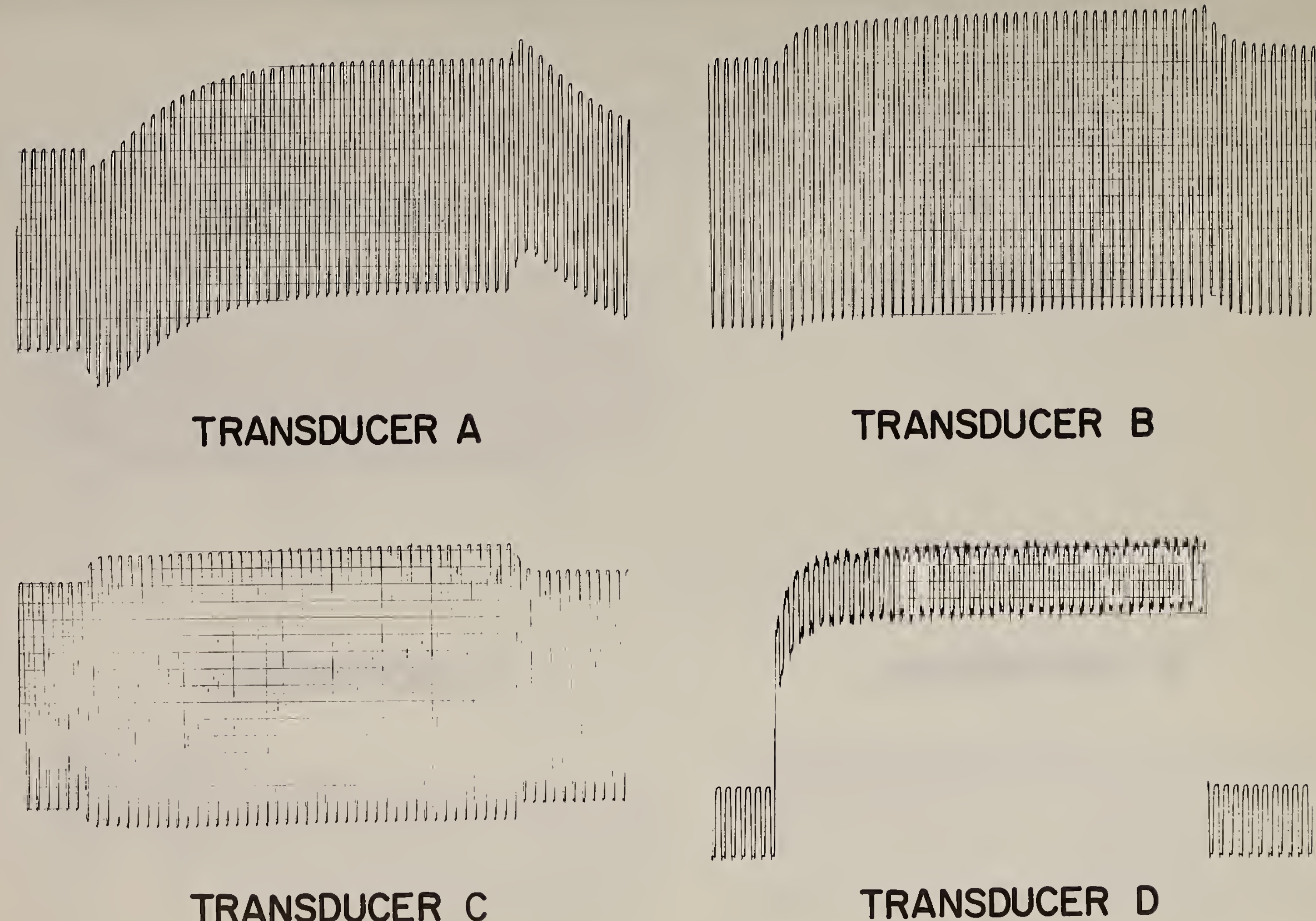


FIGURE 14. Thermal transient responses of four flush diaphragm pressure transducers, "pressure cycling technique" short term tests, at about 12.4 watts.

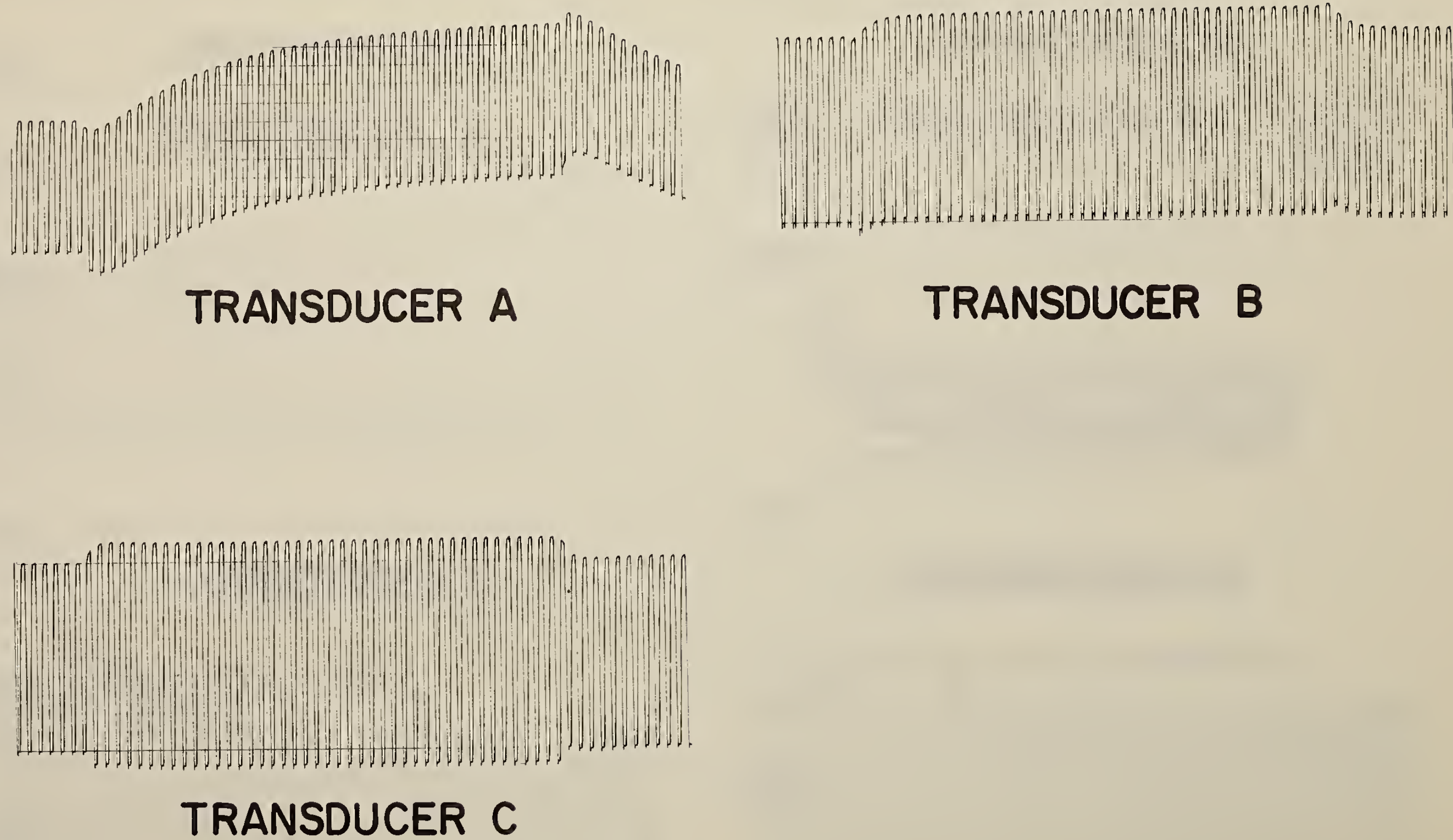


FIGURE 15. Thermal transient responses of three pressure transducers mounted in polytetrafluoroethylene plugs, "pressure cycling technique", short term tests at about 12.3 watts.

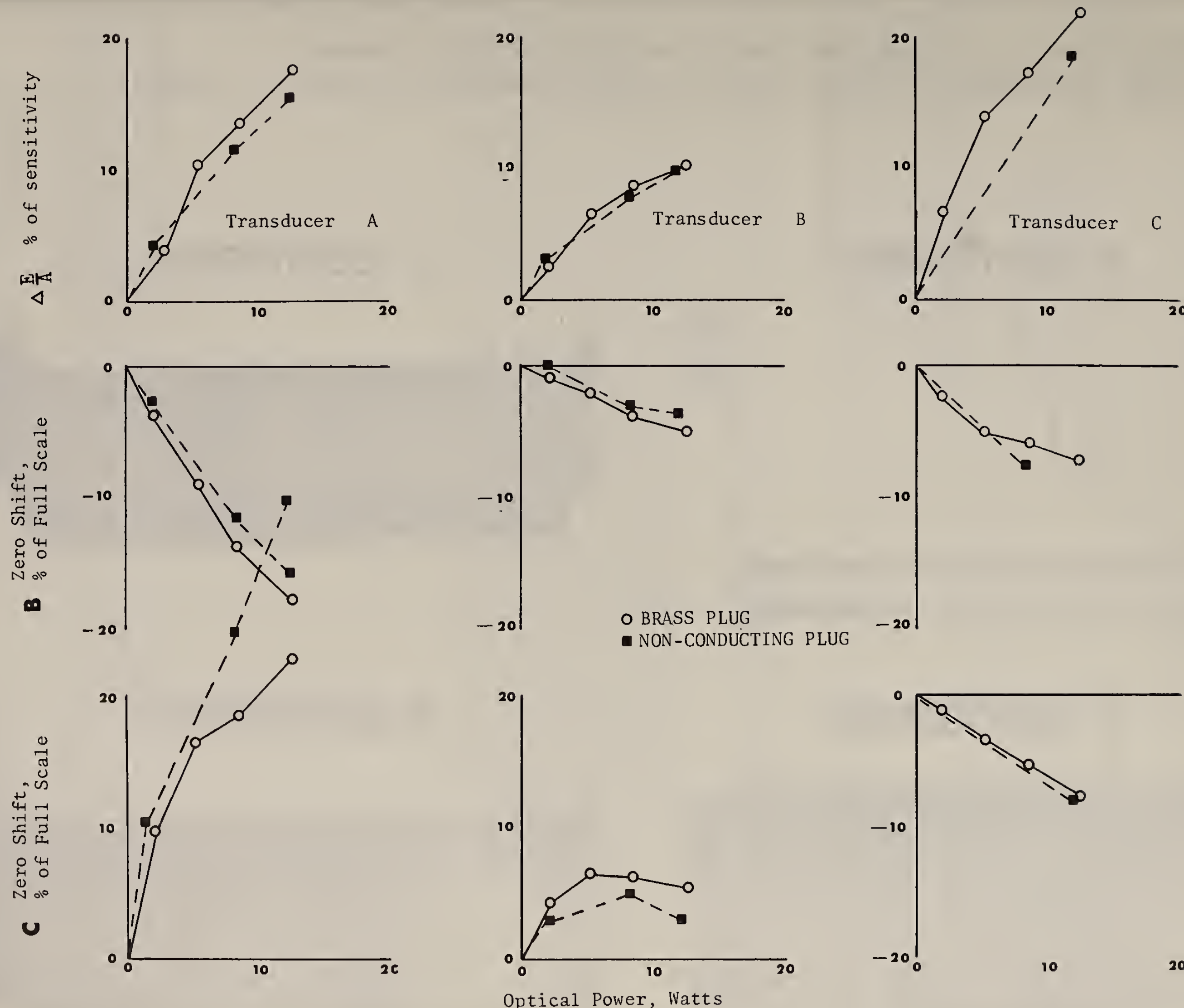
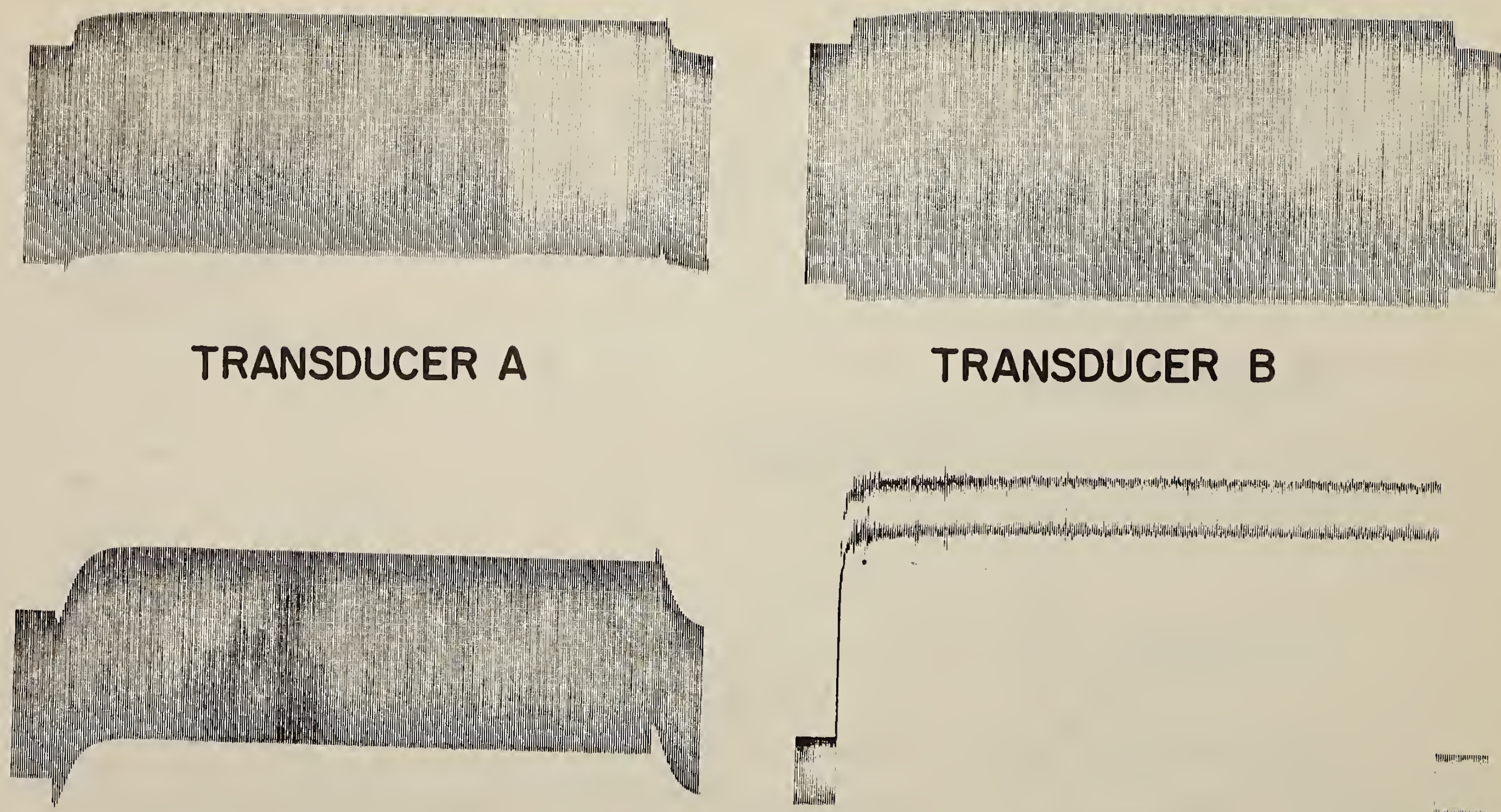


FIGURE 16. Results of short term, "zero and full scale tests" on three unbonded strain gage pressure transducers.

Reference Fig. 11 For explanation of characteristics



TRANSDUCER A

TRANSDUCER B

TRANSDUCER C

TRANSDUCER D

FIGURE 17 Thermal transient responses of four pressure transducers A,B,C,D, "pressure cycling technique", long term tests, at about 12.3 watts.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A simple and repeatable testing technique was developed which makes it practical to obtain information on the zero shift and change in sensitivity of a pressure transducer while it is subjected to a thermal transient generated by a mechanically chopped cw laser beam. Several commercial, flush diaphragm, pressure transducers with ranges from up to 50 psi (3.45×10^5 N/m^2) were tested and showed zero shifts and changes in sensitivity of the order of 20% FS due to thermal transients with power densities up to 100 K W/m^2. The transducer under test can be pressure cycled while it is irradiated. In this way, zero shifts and sensitivity changes may be directly displayed in a procedure which requires a testing time of only about one minute.

17. KEY WORDS (Alphabetical order, separated by semicolons)

Laser; performance characteristic; pressure transducer; temperature effects; test method; thermal transient.

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